Authorized Reprint from
Special Technical Testing Publication 877

Yi-Wen Cheng[1] *and David T. Read*[1]

An Automated Fatigue Crack Growth Rate Test System

REFERENCE: Cheng, Y.-W. and Read, D. T., "**An Automated Fatigue Crack Growth Rate Test System,**" *Automated Test Methods for Fracture and Fatigue Crack Growth, ASTM STP 877*, W. H. Cullen, R. W. Landgraf, L. R. Kaisand, and J. H. Underwood, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 213–223.

ABSTRACT: An automated fatigue crack growth rate (FCGR) test system has been developed that can be used for tests of constant-load-amplitude FCGR above 10^{-8} m/cycle [ASTM Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle (E 647-83)] at normal (~ 10 Hz) or low (~0.1 Hz) cyclic frequencies and for tests of near-threshold and variable-load-amplitude FCGR. The test system consists of a minicomputer, a programmable arbitrary waveform generator, a servo-hydraulic test frame, and a programmable digital oscilloscope. The crack length is measured using the compliance technique; the FCGR and the stress-intensity factor range are calculated and plotted automatically during the test.

KEY WORDS: automated test system, compliance technique, fatigue crack growth rate, fatigue of materials, near-threshold fatigue test, variable-load-amplitude fatigue test

Fatigue crack growth rate (FCGR) data are used for material characterization and for fracture mechanics reliability analysis of structures subjected to cyclic loading. A standard test method for measuring such data above 10^{-8} m/cycle under constant-amplitude loading has been developed and published in the *1983 Annual Book of ASTM Standards* under the designation ASTM E 647-83.

With the increased interest in near-threshold FCGR [*1,2*] and FCGR under environmental influences at low cyclic frequencies [*3*], the demand for FCGR measurements has increased. Obtaining such data can be tedious and time-consuming. An automated FCGR test system, such as that described in this paper, allows testing to proceed, data to be taken, and loads to be altered in the absence of an operator.

[1]Metallurgist and physicist, respectively, Fracture and Deformation Division, National Bureau of Standards, Boulder, CO 80303.

The automated test system minimizes testing time and operator attention. Data scatter is reduced owing to higher precision in crack length measurement and better control in data point spacing [*4*]. Because the testing is interactive and automatic in nature, the procedure is relatively easy to follow and requires minimal operator training. Finally, this approach eliminates subjective interpretation and influence of the experimenter.

The FCGR Test Method

The sequence of the FCGR test is: First, obtain the raw data, namely, fatigue crack length, a, versus elapsed fatigue cycles, N; then, reduce a and N data to a plot of da/dN versus ΔK, where da/dN is the FCGR in m/cycle and ΔK is the crack-tip stress-intensity factor range in MPa $m^{1/2}$. Typical outputs are presented in Fig. 1.

The number of elapsed fatigue cycles can be obtained from counters (electronic or mechanical) or conversion from time elapsed at the actual testing frequency. The methods of crack length measurement are complicated and have been a subject of extensive study [*5,6*]. Although several methods of crack length measurement have been developed, some require specialized equipment not commonly available in mechanical testing laboratories. The compliance technique, however, requires only monitoring of the load cell and the clip gage outputs, which is routinely achieved in mechanical testing. Compliance is defined as the specimen deflection per unit load, which is a function of crack length for a given material and specimen geometry. The load and deflection signals (voltages) can be interfaced to a computer. Because of the

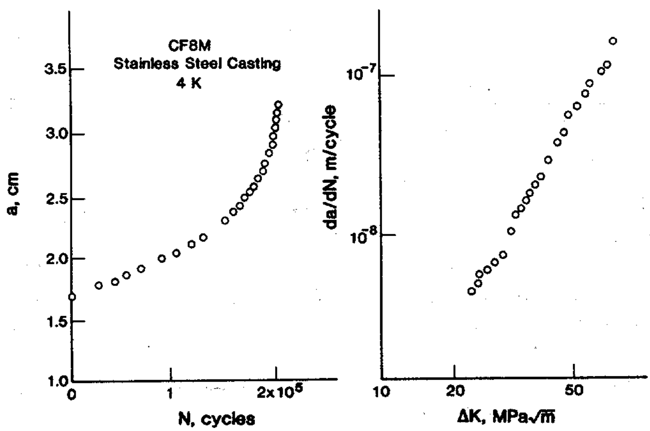

FIG. 1—*Data outputs from the automated FCGR test.*

simple instrumentation and the need in our laboratory for environmental chambers for cryogenic temperature and saltwater corrosion-fatigue tests, the compliance technique was chosen to measure the crack length.

Equipment for the Automated FCGR Test System

A schematic of the automated FCGR test system is shown in Fig. 2, which also shows the sequence of operation and interaction between various components. The test system consists of a closed-loop servo-controlled hydraulic mechanical testing machine, a programmable digital oscilloscope, a programmable arbitrary waveform generator, and a minicomputer.

The machine control unit, which is included in the hydraulic mechanical test machine, includes a servo-control system, a feedback system, two d-c conditioners, and a valve drive. A nonprogrammable function generator with an electronic pulse counter is usually built into the machine control unit of a commercially available mechanical testing machine. Signal amplifiers and a load cell are also included in the mechanical testing machine.

The programmable digital oscilloscope contains two 15-bit 100-kHz digitizers and it serves as an analog-to-digital (A/D) converter. In addition to its

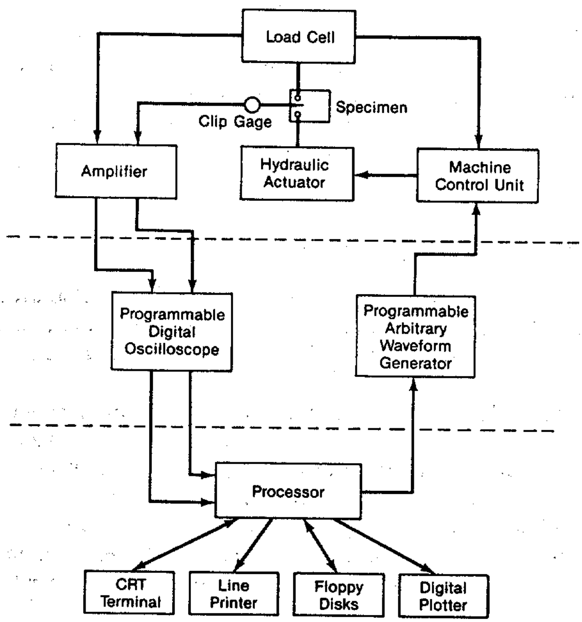

FIG. 2—*Schematic of the automated FCGR test system.*

high-speed A/D conversion rate, this oscilloscope features the ability to instantaneously freeze and hold data in memory. The problems encountered with slower A/D converters, such as interruptions during the test [7] and low test frequencies [8], are eliminated because of the high A/D conversion rate and the freeze-and-hold ability of this oscilloscope. For the near-threshold and the variable-load-amplitude FCGR tests, load levels vary with time and a programmable function generator is needed. For these tests, the programmable arbitrary waveform generator is used. The present programmable waveform generator is not connected to a cycle-counting device and the fatigue cycle counts are inferred from the cyclic frequency[2] and the time elapsed, as given by the computer. For the constant-load-amplitude FCGR test, the built-in function generator is used.

Included in the minicomputer are a cathode-ray-tube (CRT) terminal, a line printer, a dual floppy disk storage unit, and a digital plotter. The minicomputer uses the 16-bit word and has 128K words of memory. The minicomputer also contains an internal clock that reads to 1/60 s. The IEEE-488/GPIB is used for the interface between the computer and the programmable digital oscilloscope and between the computer and the programmable arbitrary waveform generator.

Applications

In the following discussion, attention is focused on how the test system described above is used to conduct the FCGR tests. Requirements on grips, fixtures, specimen design, and specimen preparation are detailed in ASTM E 647-83 and other proposed standards [3, 9] and are not discussed in this paper.

Constant-Load-Amplitude FCGR Test

The test system described in the previous section can be programmed to run the constant-load-amplitude FCGR test. The operational details, implementing the procedures set forth by ASTM E 647-83, are described in this subsection.

As shown in Fig. 3, the input parameters are fed by the operator into the computer through the CRT terminal. The input parameters include specimen identification, specimen dimensions, Young's modulus, selected time interval for measuring crack length, minimum load level for compliance measurement, load levels, and test frequency. The time interval for measuring crack length must be kept to a value small enough that every increment of crack growth will not exceed the recommended values as prescribed in ASTM E

[2]The frequency used for cycle calculations is checked with a frequency meter; the typical error in frequency is 50 ppm.

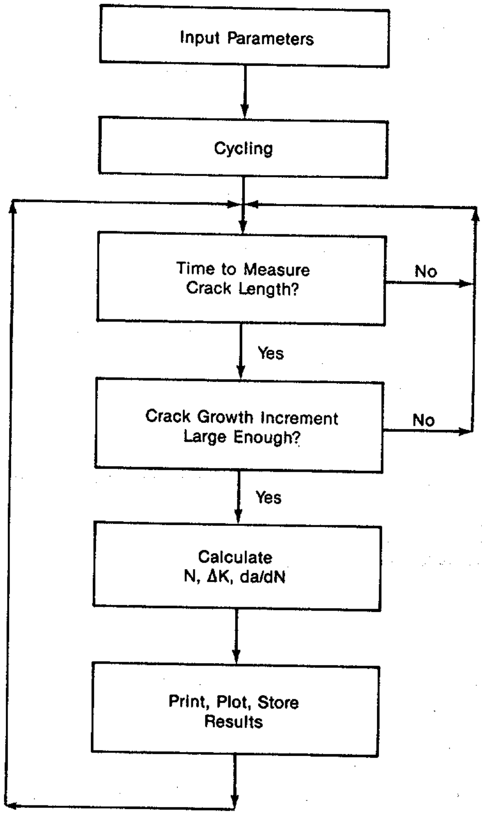

FIG. 3—*Summary flow chart of the automated constant-load-amplitude FCGR test.*

647-83. The minimum load level for compliance measurement is used to eliminate the possible crack closure effects [*10*], which have a significant effect on the accuracy of crack length measurement.

The precracked specimen is fatigue cycled under the prescribed loading conditions and cyclic frequency. A typical frequency is 10 Hz. When the preselected time interval (typical value is 1 min) for crack length measurement is reached, the computer requests the load-versus-deflection data from the programmable digital oscilloscope, which freezes the load-deflection data in the memory instantaneously, and correlates the data to a straight line using a linear least-squares fit. A linear correlation coefficient of 0.999 or better is usually obtained. From the resulting compliance, the instantaneous crack length is computed using the appropriate expression for the compliance calibration of the specimen [*11*]. The precision of the crack length measurement is typically within 0.04 mm.

The inferred crack length, which is obtained from the measured compliance, published compliance calibrations, and published Young's modulus, usually does not agree exactly with the actual crack length for a given material and specimen geometry. The exact reasons for the discrepancy between the inferred and the actual crack lengths are not clear and have been discussed in Refs *12* and *13*. Correction factors to the compliance calibration have been used to obtain more accurate physical crack length predictions.

An alternative way of correcting the mismatch between the inferred and the actual crack lengths is to adopt an "effective modulus" for the material. The effective modulus, E_{eff}, is deduced from a known crack length in a given specimen geometry and compliance calibration. Typically, E_{eff} is deduced from one well-defined crack front that is visible on a post-test fracture surface. The crack front at the end of fatigue precracking or at the final fatigue crack length is generally used. The effective modulus approach, which is used in our laboratory, thus forces agreement between the inferred and the actual crack lengths and compensates for any errors regardless of source [*13*].

The portion of the load-versus-deflection curve used for compliance calculation is from the specified minimum load level to a value corresponding to 95% of the maximum load. The typical minimum load level used for compliance calculation is the mean load (load signal midpoint). It should be noted, however, that the specific value of the minimum load level used for a given material, specimen geometry, and load ratio must be larger than crack closure loads. The reason for excluding the upper 5% of the load for calculation is that the clip gage tends to vibrate, and noise in the clip-gage signal increases at the maximum load during the high-frequency test.

The increment of crack growth (the difference between the current measured crack length and the last recorded crack length) is checked against specified values which are within the recommended values of ASTM E 647-83. A value of 0.5 mm is typically specified for a 25.4-mm-thick standard compact-type specimen. If the increment of crack growth is equal to or greater than the specified value, the computer calculates N, ΔK, and da/dN; the digital plotter plots the data points (a, N) and (da/dN, ΔK) on the a-versus-N and on the da/dN-versus-ΔK graphs, such as shown in Fig. 1; the line printer prints the value of calculated compliance, the linear least-squares correlation coefficient, a, N, da/dN, and ΔK results. All the resulting data are stored on floppy disks for post-test analyses.

During the test, the point-to-point data reduction technique is used to calculate ΔK and da/dN from a and N. Usually the results are consistent with minimum scatter, as those shown in Fig. 1. If the results of ΔK versus da/dN scatter, the seven-point incremental polynomial method is used to smooth the results after the test is completed.

The computer programs for post-test analyses include the following capabilities:

1. reducing a-versus-N data to ΔK-versus-da/dN by the seven-point incremental polynomial method,
2. converting units,
3. plotting data in desired units,
4. plotting data in desired coordinate ranges,
5. plotting data for several different specimens on one graph (for comparison), and
6. calculating the material constants C and n in the Paris equation [*14*], $da/dN = C\,(\Delta K)^n$, and drawing the regression line through the data.

All computer programs, including the data acquisition routines, were written in the PDP-11 FORTRAN language.

Near-Threshold FCGR Test

The computer programs used in the constant-load-amplitude FCGR test, with some modifications, can be used for near-threshold FCGR tests. The major difference in procedures between the two tests is that the load levels in the near-threshold FCGR test decrease according to the initial ΔK-value (in the K-decreasing test technique). The load levels are calculated from the following equations [*9*]

$$\Delta K = \Delta K_0 \exp\,[C'(a - a_0)] \tag{1}$$

$$\Delta P = B W^{1/2}\,\Delta K/f_1(a/W) \quad \text{for compact-type specimen} \tag{2}$$

$$\Delta P = B\,\Delta K/f_2(a/W) \quad \text{for center-cracked-tension specimen} \tag{3}$$

$$P_{\text{max}} = \Delta P/(1 - R);\ P_{\text{min}} = P_{\text{max}}\,R \tag{4}$$

where

P_{max} = maximum load,
P_{min} = minimum load,
R = $P_{\text{min}}/P_{\text{max}}$,
B = specimen thickness,
W = specimen width,
a = current crack length,
a_0 = crack length at beginning of test,
$f_1(a/W)$ = $[2 + (a/W)][0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]/[1 - (a/W)^{1.5}]$,

$$f_2(a/W) = [(\pi a/W^2)\sec(\pi a/W)]^{1/2},$$
ΔK = current crack-tip stress-intensity range,
ΔK_0 = crack-tip stress-intensity range at beginning of test, and
C' = negative constant.

A typical value of C' is $-0.08\ \text{mm}^{-1}$, which gives satisfactory results with no apparent anomalous crack growth for AISI 300-series stainless steels.

A flow chart describing the automated near-threshold FCGR test is summarized in Fig. 4. After each crack length measurement, the crack length is compared with the last stored crack length to ensure that a specified measur-

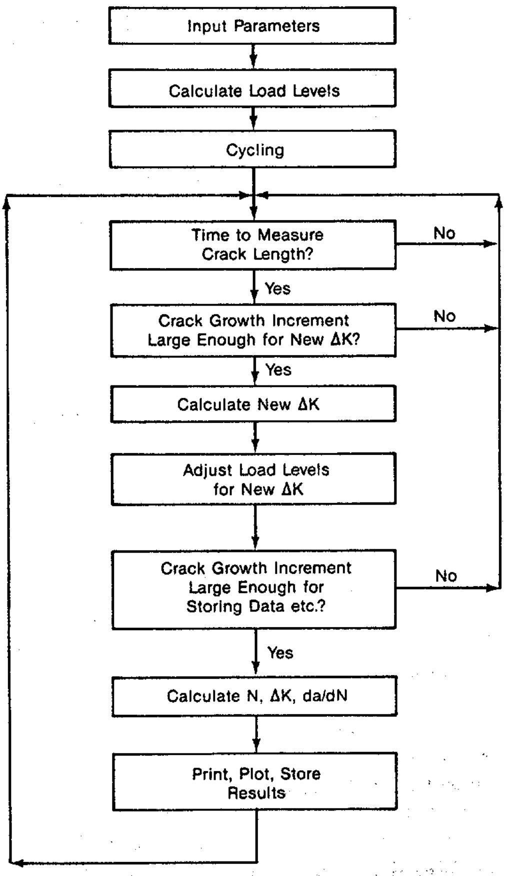

FIG. 4—*Summary flow chart of the automated near-threshold FCGR test.*

able small amount of crack growth has occurred. If this is not done, then some unnecessary load level adjustments will take place because of scatter in the crack length measurement. After the crack length has increased a certain amount (for example, 0.13 mm), the new ΔK is calculated according to Eq 1 and the new crack length is stored. The load levels are then adjusted using Eqs 2, 3, and 4.

In high-frequency fatigue testing, which is desirable in the near-threshold FCGR test, hydraulic lag might be a problem. This results in the specimen not being actually subjected to the load range commanded by the computer (or waveform generator). The problem is usually corrected by using proper signal conditioners and gain settings. However, overprogramming is sometimes necessary to overcome the persistent hydraulic lag. During the overprogramming process, which is done by trial-and-error method, the computer monitors the values of P_{max} and P_{min} through the programmable digital oscilloscope and makes necessary changes to achieve the desired values of P_{max} and P_{min}. The overprogramming is done whenever there is a hydraulic lag problem.

If the measured crack-growth increment, which is the difference between the current measured crack length and the last recorded crack length, is equal to or greater than specified values, which are within the recommended values [*8*], the values of N, ΔK, and da/dN are calculated and the results are printed, plotted, and stored. A value of 0.5 mm is typically specified for a 25.4-mm-thick standard compact-type specimen. The previously mentioned computer programs for post-test analyses are also applicable for analyzing the data obtained in the near-threshold FCGR test.

Variable-Load-Amplitude FCGR Test

The automated FCGR test system is also used in the variable-load-amplitude FCGR test. The procedures used in this application are similar to those described in the previous two subsections.

The computer reads the prerecorded load-time history from the floppy disks and controls the hydraulic machine through the programmable waveform generator. At a preselected time interval, the crack length is measured. A typical interval is 30 min for an average test frequency of 0.1 Hz. The desired output in the variable-load-amplitude FCGR test is time versus crack length. The results are printed, plotted, and stored for post-test analyses.

The present system has two limitations in the application of variable-load-amplitude FCGR testing. One is that the waveform generator needs about 0.1 s for changing one command to another, and this limits the average frequency to about 1 Hz. This will result in a situation of holding about 0.1 s at the peak loads when higher test frequencies are used. In a corrosive or a high-temperature environment, in which hold time at peak load is important, this might introduce anomalous fatigue crack growth. The other is the limited storage capacity of the floppy disks, which can store only a certain amount of load-time pairs. The present system uses soft disks, which can store about 18 000 load-time pairs. If longer load-time histories are desired, other means of storage devices such as hard disks must be used.

Summary

An automated FCGR test system has been developed that can be used for tests of constant-load-amplitude FCGR above 10^{-8} m/cycle (ASTM E 647-83), near-threshold FCGR, and variable-load-amplitude FCGR. The test system offers considerable time savings in data acquisition and in data reduction. The test procedure is relatively easy to follow and enables technicians to produce data with less scatter (with respect to the non-computer-aided technique), because higher precision in crack length measurement and better control in data point spacing are obtained, while manual data interpretation and data fitting are eliminated.

Acknowledgments

Mr. J. C. Moulder of the National Bureau of Standards is acknowledged for helpful discussions on the interface between the computer and the instruments. The work was supported by the Department of Interior, Minerals Management Service, and the Department of Energy, Office of Fusion Energy.

References

[*1*] *Fatigue Thresholds: Fundamentals and Engineering Applications*, J. Backlund, A. F. Blour, and C. J. Beevers, Eds., Engineering Materials Advisory Services, Chameleon Press, London, 1982.

[*2*] Bucci, R. J., "Development of a Proposed ASTM Standard Test Method for Near-Threshold Fatigue Crack Growth Rate Measurement," *Fatigue Crack Growth Measurement and Data Analysis, ASTM STP 738*, S. J. Hudak, Jr., and R. J. Bucci, Eds., American Society for Testing and Materials, Philadelphia, 1981, pp. 5–28.

[*3*] Crooker, T. W., Bogar, F. D., and Yoder, G. R., "Standard Method of Test for Constant-Load-Amplitude Fatigue Crack Growth Rates in Marine Environments," NRL Memorandum Report 4594, Research Laboratory, Washington, DC, Aug. 6, 1981.

[*4*] Wei, R. P., Wei, W., and Miller, G. A., "Effect of Measurement Precision and Data-Processing Procedure on Variability in Fatigue Crack Growth-Rate Data," *Journal of Testing and Evaluation*, Vol. 7, No. 2, March 1979, pp. 90–95.

[*5*] *The Measurement of Crack Length and Shape During Fracture and Fatigue*, C. J. Beevers, Ed., Engineering Materials Advisory Services, Chameleon Press, London, 1980.

[*6*] *Advances in Crack Length Measurement*, C. J. Beevers, Ed., Engineering Materials Advisory Services, Chameleon Press, London, 1981.

[*7*] Cheng, Y.-W., "A Computer-Interactive Fatigue Crack Growth Rate Test Procedure," *Materials Studies for Magnetic Fusion Energy Applications at Low Temperatures—VI*, R. P. Reed and N. J. Simon, Eds., NBSIR 83-1690, National Bureau of Standards, Boulder, CO, 1983, pp. 41–51.

[*8*] Ruschau, J. J., "Fatigue Crack Growth Rate Data Acquisition System for Linear and Non-

linear Fracture Mechanics Applications," *Journal of Testing and Evaluation*, Vol. 9, No. 6, Nov. 1981, pp. 317-323.

[9] "Proposed ASTM Test Method for Measurement of Fatigue Crack Growth Rates," *Fatigue Crack Growth Measurement and Data Analysis. ASTM STP 738*, S. J. Hudak, Jr. and R. J. Bucci, Eds., American Society for Testing and Materials, Philadelphia, 1981, pp. 340-356.

[10] Elber, W., "The Significance of Fatigue Crack Closure," *Damage Tolerance in Aircraft Structures, ASTM STP 486*, M. S. Rosenfeld, Ed., American Society for Testing and Materials, Philadelphia, 1971, pp. 230-242.

[11] Hudak, S. J., Jr., Saxena, A., Bucci, R. J., and Malcolm, R. C., "Development of Standards of Testing and Analyzing Fatigue Crack Growth Rate Data," AFML-TR-78-40, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, May 1978.

[12] Nicholas, T., Ashbaugh, N. E., and Weerasooriya, T., "On the Use of Compliance for Determining Crack Length in the Inelastic Range," *Fracture Mechanics: Fifteenth Symposium, ASTM STP 833*, R. J. Sanford, Ed., American Society for Testing and Materials, Philadelphia, 1984, pp. 682-698.

[13] Tobler, R. L., and Carpenter, W. C., "A Numerical and Experimental Verification of Compliance Functions for Compact Specimens," to be published in *Engineering Fracture Mechanics*.

[14] Paris, P. C., and Erdogan, F., "A Critical Analysis of Crack Propagation Laws," *Transactions*, American Society of Mechanical Engineers, *Journal of Basic Engineering*, Series D, Vol. 85, No. 3, 1963, pp. 528-534.